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An overview for energy recovery from municipal solid wastes (*MSW*) in Malaysia scenario

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ABSTRACT

Uncontrolled emission of greenhouse gases (GHGs) to the atmosphere leads to climate change. One of the key contributors in GHG emission is municipal solid waste. Increasing population and rapid urbanisation in Malaysia directly influence *MSW* generation that has increased from 5.6 million tonnes in 1997 to more than 8 million tonnes in 2010 with a projection of more than 9 million tonnes by 2020. There are 6 operational sanitary landfills out of the 104 in operation in Peninsular Malaysia with five of them recovering methane. With a biodegradable component of more than 60%, *MSW* landfills are potential sources of cheaper and cleaner landfill gas (LFG). 310,225 t of methane were emitted from the *MSW* landfills in 2010 with carbon credit potential of US$85.93 million and can yield 2.20×10^9 kW h of electricity valued at US$219.50 million. Emission projections were made for the years 2015 and 2020. The analysis points to a very promising and viable resource utilisation potential that will be of economic and environmental benefits. It will also create job opportunities for the local community. The use of this LFG will provide the means for overall GHG reductions and boost the efforts to achieve sustainable development.

Contents

1. Introduction

The world is battling with the problems of increasing global surface temperature [1] due to climate change occasioned by human activities [2,3]. These uncontrolled human activities have led to the emission of greenhouse gases (GHGs). The continuous

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emissions of these gases have resulted in significant and negative global impacts on people, natural resources and economic conditions [4–7] and increased environmental degradation [8]. Methane (CH_4) and carbon dioxide (CO_2) ar the two gases chiefly responsible for this temperaure increase [9]. Though methane concentration in the atmosphere is lower than that of carbon dioxide, it is 21–25 times more powerful than CO_2 [10,11] and account for 20% of global greenhouse gas effect [12]. The global anthropogenic emissions for methane from all sectors in 2010 were estimated to be 6875 million metric tons CO_2 equivalent (Mt CO_2eq) [13,14]. Methane is emitted naturally by termites, grasslands, coal beds, lakes, wetlands and wildfires and by anthropogenic (human) sources from landfills, oil and gas processing, watsewater treament plants, coal mining, rice production, cattle ranching and agricultural activities [15] one distinct advantage of methane is that it is a 'green fuel' and can be used to generate electricity, as fertilizer and methanol production feedstock and as a source of heat [8].

The disposal of solid wastes in landfills leads to methane generation by anaerobic degradation of the organic contents of the waste and the volume of gas produced is affected by the management method employed [16]. The emission of this gas has become significant environmental and energy issues in relation to deposition of municipal solid waste (*MSW*) in landfills. Molecular solid waste landfills are among the largest anthropogenic sources of methane. In the US landfills emit about one-third of all methane emitted [17].

The growing economy has led to increase in energy demand that has also led to a change in consumption pattern among the populace [18]. Energy is essential to economic and social development as well as leading to improved quality of life [19]. Unfortunately, much of the energy in current use are fossil fuel based whose present technology are not sustainable. In Malaysia, a 1% growth in GDP is said to be accompanied by a corresponding growth in energy demand of 1.2–1.5% [20]. Energy from waste will create diversion from landfills while saving significant greenhouse gas emissions as the energy generated will replace equivalent amount of energy from fossil fuels.

This work reviews the waste generation and methane emission patterns in Malaysia. The review also considers the energy potential of the landfill gas and looks at the potential economic benefits of harnessing the methane as a basis for sustainable waste management.

2. Methane generation process in a landfill

The main degradation products from a landfill are carbon dioxide (CO_2), water and heat for the aerobic process, and methane (CH_4) and carbon dioxide (CO_2) for the anaerobic process [21]. CH_4 and CO_2 are also the major landfill gases (LFG) with relative amounts of 40–45% and 55–60% by volume, respectively, for CH_4 and CO_2 [22] while some authors put the values at 50–60% and 30–40% by volume [23]. The factors that influence methane generation in landfill are the composition of the waste and availability of readily biodegradable organic matter, the age of the waste, moisture content, pH and temperature [24]. Three processes that lead to the formation of landfill gas are bacterial decomposition, volatilization, and chemical reactions [25].

Municipal solid waste is the biggest environment problem facing Malaysia [26] with various generation rates that vary from 0.5–0.8 to 1.7 kg/person/day [27–29]. The daily waste generation has also shown an upward trend. The daily waste generation was 16,200 t in 2001. This increased to 19,100 t in 2005, 17,000 t in 2007, 21,000 t in 2009 and is projected to reach 31,000 t/day by 2020 [27,30,31]. For high income countries the waste generation is 2.75–4.00 kg/person/day and is 0.5 kg/person/day for low income countries [32]. The annual waste generation for certain years are presented in Table 1 with projection made for 2015 and 2020 [26,33,34]. The increase is expected because of the increasing Malaysian population and the economic boom being enjoyed by the people. Fig. 1 shows the daily waste generation for each state from 1996 to 2008 [35]. It could be seen that the state of Selangor has been the highest generator of waste all along followed by FT Kuala Lumpur. These areas have the highest population density in the country.

Table 1
Annual waste generation in Malaysia.

Year	Amount (tonnes)
1997	5600,000
1998	6000,000
1999	6105,000
2000	6369,000
2005	6970,000
2006	7340,000
2007	7655,000
2010	8196,000
2015**	9111,000
2020*	9820,000

* Projected values.

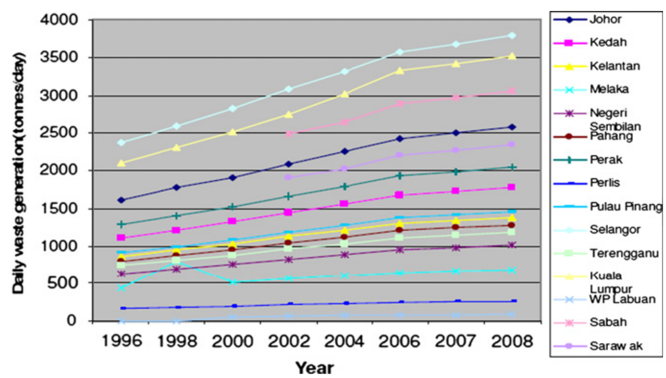


Fig. 1. Daily waste generation according to states in Malaysia (1990–2008).

Table 2
Typical characterisation of Malaysian *MSW* (%).

Material	[37]	[38]	[27]	[39]	[25]	[40]
Food/organic	59.2	36.6	37.43	68.67	57.0	45.0
Plastic	12.6	30.7	18.92	11.45	15.0	24.0
Paper	8.0	8.9	16.78	6.43	17.0	7.0
Textile	1.4	1.0	8.48	1.50	1.0	–
Wood	2.3	0.3	3.78	0.70	–	–
Yard waste	7.6	6.7	3.18	–	5.0	–
Rubber	0.7	–	1.32	–	1.0	–
Glass	1.6	2.8	2.68	1.41	1.0	3.0
Organic fines	4.0	–	4.37	–	1.0	–
Aluminium/metals	2.4	12.1	3.40	2.71	2.0	6.0
Others	–	0.9	7.16	7.13	–	15.0
Total	100.0	100.0	100.00	100.00	100.0	100.0

3. Municipal solid waste characterisation

Waste is characterised in order to decide the best management option to adopt [8]. Characterisation also allows for the estimate of biodegradable organic carbon and to monitor the effectiveness

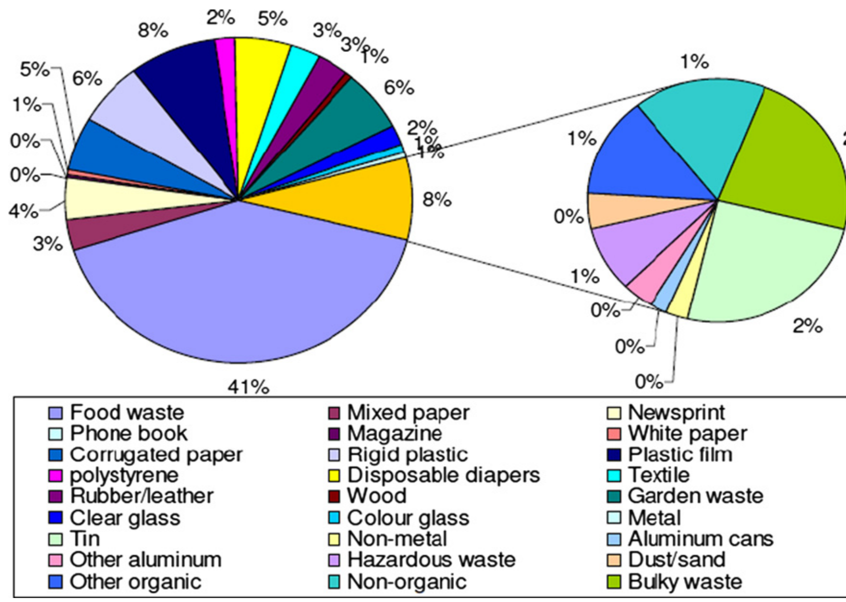


Fig. 2. Average composition of *MSW* generated in Malaysia.

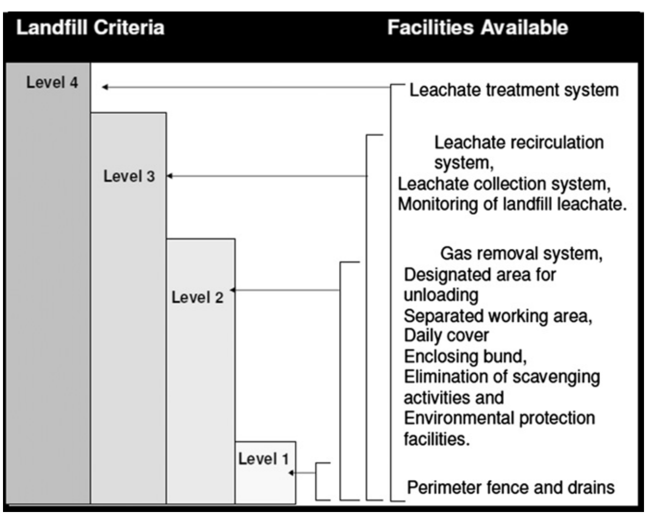


Fig. 3. Classification of different level of landfills in Malaysia.

Table 3
Operational and non-operational landfill distribution in Malaysia.

State	Landfills in operation	Landfills not in operation
Johor	13	21
Kedah	10	5
Kelantan	13	4
Melaka	2	5
Negeri Sembilan	8	10
Pahang	19	13
Perak	20	9
Perlis	1	1
Pulai Pinang	1	2
Sabah	21	1
Sarawak	51	12
Selangor	6	12
Terengganu	9	12
FT Kuala Lumpur	1	7
FT Labuan	1	0
FT Putrajaya	0	0
Total	**176**	**114**

of programmes designed to divert recyclable and compostable materials from landfills [36]. Typical characterisation of Malaysian *MSW* by different authors is presented in Table 2. The table shows the changing pattern of waste generation. The percentage of food waste has increased from 37% in 2004 to 59% by 2009. The amounts of paper and plastic have also reduced substantially except one investigator [26] who gave a high value for paper waste. The large percentage of biodegradable organic matter (food waste and paper) creates a favourable environment for landfill gas generation or composting. The factors for this increased waste generation have been attributed to the tremendous population growth, the rapid urbanisation process, the increasing urban population, the relatively young age structure of the population, rapid economic growth, and, the multi-racial nature of the society [34]. Figs. 2 and 3.

Landfills are said to generate 53% of methane emissions in Malaysia with palm-oil mill effluent, swine manure and industrial effluent generating 38%, 6% and 3%, respectively [37]. The total methane emission from waste sectors in Malaysia is given as 1.3 Gg yr^{-1} [16] with the methane emission in 1994 being 2.2 Gg [37].

4. Management of landfills in Malaysia

The landfills in Malaysia were initially under the Local Authorities (Section 72, Local Government Act 1976). They have since been placed under the Ministry of Housing and Local Government (MHLG). In Action Plan 1988, the government has tried stepwise increase in the efficiency of disposal sites by creating four targeted levels of improvement [27]. These levels are:

- Level 1: Controlled dumping.
- Level 2: Sanitary landfill with daily cover.
- Level 3: Sanitary landfill with leachate circulation.
- Level 4: Sanitary landfill with leachate treatment.

The privatisation of solid waste management in 1996 led to the creation of three solid waste concessionaries with different operational zones: Idaman Bersih Sdn Bhd for northern regions, Alam Flora Sdn Bhd for central regions and Southern Waste Management for southern regions [27].

In 2005, the first comprehensive policy on waste management was published. It entitled National Strategic Plan for Solid

Table 4
Existing sanitary landfills (SLF) and characteristics in Malaysia.

Facility	State	Condition	Waste in place (2009) (10^3 t)	Current CH_4 status	Year CH_4 reduction started	Average CH_4 emission reduction (t CO_2eq)
Pulai	Kedah	In operation	440	No recovery	–	–
Ampang Jajar	Pinang	Closed	3,360	No recovery	–	–
Pulai Burung	Pinang	In operation	19,050	Passive aeration	2010	45,538
Johor Jerangau	Pahang	In operation	2,920	Recovering	2008	15,418
Air Hitam	Selangor	Closed	1,610	No recovery	–	–
Kg. Hang Tuah	Selangor	Closed	530	No recovery	–	–
Jeram	Selangor	In operation	1,500	No recovery	–	–
Bukit Tagar	K. Lumpur	In operation	2,850	Recovering	2009	219,625
Krubong	Melaka	Closed	4,100	Recovering	2007	57,830
Seelong	Johor	In operation	2,500	Recovering	2007	108,335
Meradong	Sarawak	In operation	40	No recovery	–	–
Sibuti	Sarawak	In operation	300	No recovery	–	–
Kuching	Sarawak	In operation	820	Recovering	2009	48,507
Kemunyang	Sarawak	In operation	410	No recovery	–	–

Waste Management in Malaysia (NSP 2005). The policy proposed an integrated municipal solid waste management that will practice a waste management hierarchy prioritizing waste reduction through the 3R's i.e., reduce, reuse, recycle at both pre- and post-consumer stage. One highlight of the policy is the enacting of the Solid Waste and Public Cleansing Management Act 2007 (Act 672) which empowers the Director General of the Department of National Solid Waste Management to direct and control the solid waste to be separated, handled and stored. Failure to comply with this directive is liable to a fine not exceeding RM1000.00 (US$350.00) [42].

Section 102 of the Act compels manufacturers to retrieve their products or goods after use by consumers at their own expense. The Act came into force on Sept., 1 2011. Initially the 'penalty for not separating solid waste is not mandatory' as it is designed to allow the public to get familiar with the solid waste separation practice. The Act also empowers the management of solid waste to three concessionaries: Environment Idaman Sdn Bhd, Alam Flora Sdn Bhd and SWM Environment Sdn Bhd to manage solid wastes in the northern, central and southern parts of Peninsular Malaysia [42].

5. Landfill facilities in Malaysia

The evolution of landfill facilities has been traced. In 1988 there were only 49 landfills in operation. These increased to 155 in 2001, 161 in 2002 and 176 by 2007 [43,44]. These are functional landfill sites. Presently there are 176 operational and 114 non-operational landfill sites in Malaysia [41]. Table 3 shows the distribution of the numbers operational and non-operational landfills in each state and the Federal Territories in Malaysia [41]. These landfills facilities vary in capacities between 8 and 60 ha [8]. Most of these facilities are mere open dumpsites with overloaded capacities. The non-sanitary nature of these facilities have led to serious environmental problems like fire outbreak, pollution of rivers and underground facilities by leachate, and other health-related problems. The solution to these problems lies in the ability to upgrade the landfill to sanitary status (i.e., levels 3 and 4) where the gas generated could be trapped and captured for use or otherwise. This will be a boost to government efforts in promoting the use of renewable energy and introducing energy efficiency into the system as enshrined in the policy instruments for the promotion of renewable energy and energy efficiency in Malaysia.

Only ten landfills are of sanitary status in Peninsular Malaysia and four are in Sarawak. The characteristics of the sanitary landfills are shown in Table 4 [16]. Methane recovery is taking place in five out of the six operational landfills some while only one facility is recovering methane in Sarawak. The Pulau Burung facility has the largest amount of *MSW* disposal of 19,050,000 t and recovers 45,538 t CO_2eq while the Bukit Tagar facility has the highest methane recovery potential of 219,625 t CO_2eq with 2850,000 t of waste deposited so far. These two facilities are still in operation [16].

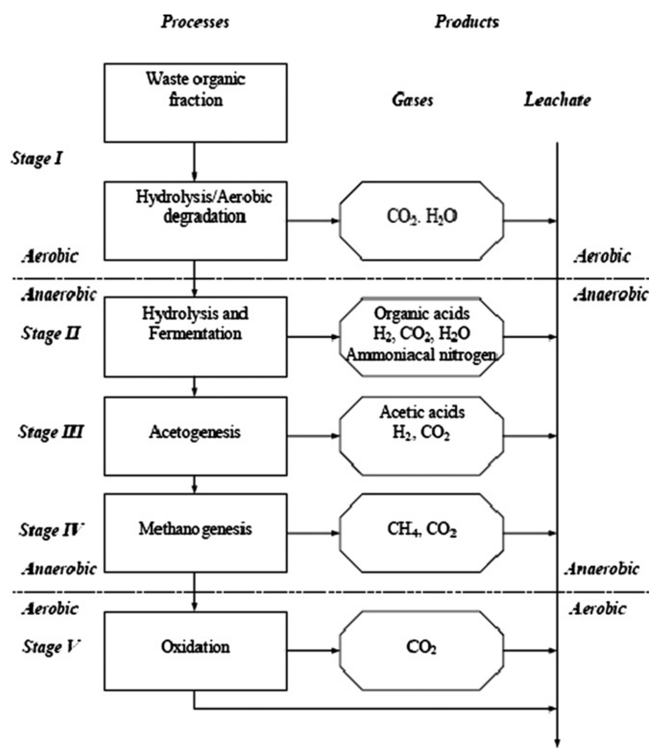


Fig. 4. Major stages of waste degradation in landfills.

6. Methane generation process in a landfill

The main degradation products from a landfill are carbon dioxide (CO_2), water and heat for the aerobic process, and methane (CH_4) and CO_2 for the anaerobic process [45]. Three processes that lead to the formation of landfill gas are bacterial decomposition, volatilization, and chemical reactions [25].

The degradation of organic matter into methane occurs in five phases [25,46]. The five phases of bacterial decomposition are shown in Fig. 4 [47]. They are:

Phase I (*Hydrolysis/Aerobic degradation*)**:** In the first phase enzymes excreted by hydrolytic microorganisms solubilise complex solid organic material. In this phase of decomposition, aerobic bacteria consume oxygen while breaking down the long molecular chains of complex carbohydrates, proteins, and lipids that comprise organic waste. The primary by-products of this process are carbon dioxide, water and heat [48].
Phase II (*Hydrolysis and fermentation*)**:** In the second phase, there is conversion of soluble organic components including the products of hydrolysis into organic acids and alcohols. Phase II decomposition starts after the oxygen in the landfill has been used up. There is the growth of a facultative bacterium that can survive in aerobic and anaerobic conditions. Hydrolysis of carbohydrates, proteins and lipids to sugars take place and these decompose to carbon dioxide, hydrogen, ammonia and organic acids [48].
Phase III (*Acidogenesis/acetogenesis*)**:** Using an anaerobic process, organic acids created by aerobic bacteria are converted into acetic, lactic, and formic acids, alcohols (methanol and ethanol), hydrogen and carbon dioxide by bacteria [47] and the landfill becomes highly acidic. Certain nutrients are dissolved by the acids as they mix with the moisture present in the land-fill, and make nitrogen and phosphorus available to the increasingly diverse species of bacteria in the landfill leading to the release of carbon dioxide and hydrogen. If there is disturbance or the introduction of oxygen into the landfill, the microbial processes will return to phase I.
Phase IV (*Methanogenesis*)**:** In the fourth phase there is the conversion of the products of acidogenesis/acetogenesis into acetic acid, hydrogen and carbon dioxide. This phase starts when certain kinds of anaerobic bacteria consume the organic acids produced in phase III and form acetate, an organic acid. This process causes the landfill to become a more neutral environment in which methane-producing bacteria begin to establish themselves. There is symbiosis between methane- and acid-producing bacteria and because of this, the acid-producing bacteria create compounds for the methanogenic bacteria to consume. The carbon dioxide and acetate are consumed by methanogenic bacteria, too much of which would be toxic to the acid-producing bacteria. In the anaerobic stage, anaerobic degradation of organic substances generate a large amount of landfill gas, primarily methane and carbon dioxide, as well as other trace gases like H_2S, N_2O and CO [9].
Phase V (*Oxidation*)**:** In the fifth phase, there is an aerobic condition occurs and the aerobic microorganisms convert the methane in the last phase to carbon dioxide and water. Hydrogen sulphide may form in waste with a high concentration of SO_4^{-2} [48].

7. Methane emission estimate from landfills

The chemical formula $C_6H_{10}O_4$ is said to closely approximate the mix of organic wastes in *MSW*. It is a representative formula corresponding to that of not less than 10 organic compounds that includes adipic acid and ethylene glycol diacetate [49]. Hence, anaerobic decomposition of *MSW* to yield LFG can be represented by the reaction [8].

$$C_6H_{10}O_4 + 1.5H_2O \rightarrow 3.25CH_4 + 2.75CO_2 \quad (1)$$

Adipic acid (waste)

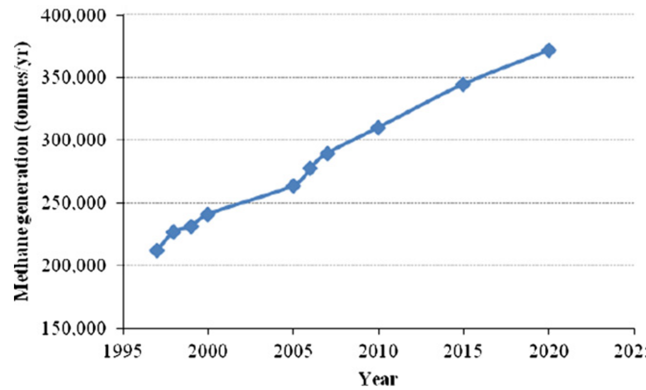


Fig. 5. Actual and projected methane generation.

The equation indicates that the ratio of waste to water is 5.4:1 with a typical waste said to contain 69.5% biomass or 60% dry biomass with the exclusion of inorganic dirt and moisture. The method proposed by the Intergovernmental Panel on Climate Change (IPCC) for the estimation of methane emission from waste disposal sites by default method is given by [50]:

$$Q = \left(MSW_T \times MSW_F \times MCF \times DOC \times DOC_F \times F \times \frac{16}{12} - R \right)(1-OX) \quad (2)$$

where Q=total methane emissions (Gg/yr).

MSW_T=Total solid waste generated (Gg/yr).
MSW_F=fraction of solid waste disposed to landfill.
MCF=methane correction factor (fraction).
DOC=degradable organic carbon (fraction).
DOC_F=dissimilated organic fraction (i.e., fraction converted to LFG).
F=fraction of CH_4 in landfill gas.
R=recovered CH_4 (Gg/yr).
16/12=molecular weight ratio of methane and carbon.
OX=oxidation factor (fraction).

Since about 80% of the total *MSW* generated in Malaysia is sent to the landfill, MSW_F is taken as 0.8 [51]. The default value for *MCF* is 0.6 for uncategorised *SWDS* [48] while the default value for *DOC* is 0.14 (IPCC, [50]). The biodegradation of *DOC* is not total, hence the default value of DOC_F is taken as 0.77 [52]. The amount of methane in LFG is taken as 55%, hence F=0.55. It is assumed that no methane recovery takes place and so R is zero while the oxidation factor is also zero. When these values are combined with Table 1 and put in Eq. (2), a methane generation profile is obtained (Fig. 5). The increasing trend of the emission is very evident. From a value of 212,000 t in 1997, there has been a steady rise in methane emission with time. The emission was 241,000 t in 2000 and rose to 264,000 t by 2005. In 2010 the emission was 310,000 t and is projected to reach 345,000 and 372,000 t in 2015 and 2020, respectively. These values are in close agreement with an earlier investigation that predicted values of 318,800 and 397,700 t for 2009 and 2020, respectively [16].

8. Energy recovery, economic and environmental benefits

8.1. Energy recovery

LFG is one of the few renewable resources that cause direct pollution reduction to the atmosphere. It is a reliable, renewable, local fuel source and brings about reduction in the need for fossil

Table 5
Energy potential of methane emission.

Year	CH_4 emitted (tonnes)	[a]CO_2 equivalent (Mt CO_2eq)	[b]Revenue from carbon credit ($\times$ 10^6 \$)	Volume of CH_4 ($\times 10^6$ m^3)	[c]Calorific value ($\times 10^9$ MJ)	[d]Equivalent electricity generation ($\times 10^9$ kW h)	[e]Revenue from electricity ($\times 10^6$ \$)
1997	211,967	4.45	58.74	317.79	5.40	1.50	149.85
1998	227,104	4.77	62.96	340.49	5.79	1.60	160.07
1999	231,079	4.85	64.02	346.44	5.89	1.53	163.45
2000	241,071	5.06	66.79	361.43	6.14	1.70	170.34
2005	263,820	5.54	73.13	395.53	6.72	1.86	186.48
2006	277,824	5.83	76.96	416.53	7.08	1.97	196.47
2007	289,747	6.08	80.26	434.40	7.38	2.05	204.80
2010	310,225	6.51	85.93	465.10	7.91	2.20	219.50
2015	344,858	7.24	95.57	517.03	8.78	2.44	243.65
2020	371,696	7.81	103.09	557.27	9.47	2.63	262.79

[a] Based on GWP of 21 for methane.
[b] At a cost of US\$23.20/tonne of CO_2.
[c] Calorific value of 17 MJ/m^3 of methane.
[d] 1 MJ=0.2775 kW h.
[e] At US\$0.1/kW h.

fuels. Methane from *MSW* is a source of energy that is 'free' and mostly cleaner than conventional energy sources. The LFG composition is 55% methane with a density of 0.667 kg/m^3 at 30 °C and a LFG calorific value of 17 MJ/m^3 [53]. These were used to determine the calorific values of methane using the data in Fig. 5. The results are shown in Table 5.

This is therefore a potential resource that could be harnessed. The primary use of the landfill gas is the energy supply, and secondary uses are prolonged site life, social impact, environmental benefits and economic empowerment. Using a GWP of 21 and US\$13.20/tonne CO_2 [8], the equivalent CO_2 reduction and revenue from carbon credit are shown in columns 3 and 4 of Table 5. With a CO_2 emission reduction of 6.51 Mt CO_2eq for 2010, the reduction is expected to be 7.24 and 7.81 Mt CO_2eq by 2015 and 2020, respectively. These will translate to carbon credit revenues of US\$85.93, 95.57 and 103.09 million, respectively for 2010, 2015 and 2020.

In similar vein, the equivalent electricity that could be generated from the LFG is 2.20×10^9 kW h for 2010 alone which translates to about 1.5% of Malaysia energy requirement [54] and is said to be equivalent to supplying the electricity needs of 420,000 Malaysians [8]. This electricity generation is projected to be 2.44×10^9 kW h and 2.63×10^9 kW h for 2015 and 2020, respectively. This will be a relief as the energy demand in 2010 is almost 100% the 1999 level [55].

8.2. Economic benefits

Apart from its high GWP, positive use of methane will also bring about reduction in ozone layer depletion. In monetary terms at US\$0.1/kW h (RM0.31/kW h) [56], the electricity generated from the LFG could fetch revenues of US\$219.50 $\times 10^6$, US\$243.65 $\times 10^6$ and US\$262.79 $\times 10^6$, respectively for the years 2010, 2015 and 2020.

Carbon dioxide contributes by volume a significant percentage of LFG. If the gas is allowed to pass through a filtering process, it could be recovered at minimal costs and made available to carbon dioxide users.

LFG energy projects will lead to the creation of jobs that are associated with the design, construction, and operation of energy recovery systems.

8.3. Environmental benefits

Uncontrolled surface emissions of landfill gas into the air are the biggest health and environmental concerns. With LFG energy projects, there is assurance of cleaner air and reductions of smog, odour, and greenhouse gas emissions. The community and all project partners benefit from using LFG because energy projects help to ensure proper management of local landfills. Utilising LFG will reduce subsurface migration from landfills to other areas within the landfill property or outside the landfill property with the attendant reduction in fire and explosion hazard. The use of LFG as cleaner fuel source will minimise the impact of fossil fuels to emit polluting materials harmful to the ozone layer, flora and fauna.

While other power plants rely on water for cooling, LFG power plants are usually very small, and therefore their pollution discharges into receiving water bodies are small.

9. Conclusion

Malaysia is trying to diversify her energy base by having a broad mix. Renewable energy is one of the promising alternatives and LFG have been shown to offer excellent opportunities. This will reduce over-dependent on non-renewable fossil fuels with their attendant unstable prices and occasional supply interruptions. Landfill gas recovery will provide a highly effective means of reducing overall greenhouse gas emissions from landfills. The methane contained in the collected landfill gas will be used to generate electricity or directly as a fuel displace fossil fuels such as oil and coal which is an environmental benefit. This is also a boost for the utilisation of alternative fuels programme which also have the added benefit of extending the life of the landfill through volume reduction in the form of energy.

Methane emission from the landfill for 2010 was 310,225 t and is projected to reach 345,000 and 370,000 t by 2015 and 2020, respectively. These values are equivalent to 2.20×10^9, 2.44×10^9 and 2.63×10^9 kW h of electricity and are expected to generate revenues of US\$219.50, 243.63 and 262.79 million, respectively. In terms of carbon credits, these could fetch US\$85.93, 95.57 and 103.09 million, respectively, for 2010, 2015 and 2020. These signify huge economic potentials for the country.

The availability of cleaner and cheaper energy will reduce environmental pollution and lead to job creation for the local community. Effective mitigation of methane emission is important and will lead to the provision of environmental benefits and sustainable development while at the same time reducing adverse impacts on human health.

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